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**ON THE CONTROL OF STRUCTURES BY
APPLIED THERMAL GRADIENTS**

Don Edberg

Jay-C. Chen

**Applied Technologies Section
Jet Propulsion Laboratory
California Institute of Technology**

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The passive damping of large space structures is expected^{1,2} to be small, on the order of about 1%. This figure is small enough that the performance of orbiting structures such as reflectors, antennae, and others with stringent pointing requirements will be hindered by the long settling time necessary for the subsidence of disturbances. We expect that some increase of damping will be required. This presentation discusses one prospective method.

- [1] Edberg, D., "Measurement of Material Damping In a Simulated Space Environment," Stanford Dept. of Aero/Astro Report No. 546, Dec. 1984.
- [2] Ashley, H., and Edberg, D., "On the Virtues and Prospects for Passive Damping in Large Space Structures," Paper DA, Proceedings of Vibration Damping Workshop II, Las Vegas, NV, Feb. 1986.

Passive Damping of Large Space Structures

- In general, passive damping is small ($\zeta \approx 1\%$).
- More damping is required for “reasonable” performance.

A variety of techniques exist to control spacecraft. There are three different control problems which have to be considered: rigid-body pointing (attitude control), shape control, and vibration suppression. Conventional type actuators, such as thrusters and momentum wheels are satisfactory for attitude control. Thrusters use consumables, and reaction wheels can "saturate". Neither is suitable for shape control or vibration suppression.

For these categories, we need a so-called "internal" actuator, which does not produce inertial forces - only internal forces in the body. Two possible candidates are piezoelectric actuators^{3,4}, and thermoelectric actuators. We shall present some of our work on thermoelectric actuators.

- [3] See, for example, "Use of Piezo-Ceramics as Distributed Actuators in Large Space Structures," by Crawley and de Luis, Paper 85-0626, AIAA 1985 SDM Conference, Orlando, FL.
- [4] Refer to the presentation "Vibration Suppression by Stiffness Control," by Fanson and Chen in the proceedings of the present conference.

Methods of Increasing Damping

- “External” type actuators (inertial)
 - Thrusters
 - Control Moment Gyros and Pivoting Proof Masses
- Internal Actuators (produce no external forces)
 - Piezoelectric actuators
 - Thermoelectric actuators

There is good reason to try to control by using thermal-type actuators. Several works^{5,6} have shown that material damping occurs because of a lag in conversion of vibrational to heat energy. In addition, civil engineers have known for years that thermal loading can produce very large forces.

- [5] Ashley, H., "On Passive Damping Mechanisms in Large Space Structures," **Journal of Spacecraft and Rockets**, Sept./Oct. 1984.
- [6] Lee, U., "Thermoelastic and Electromagnetic Damping Analysis," **AIAA Journal**, Nov. 1985.

Motivation for Thermal-Type Actuators

- Material damping occurs because of energy conversion between vibrational and heat
- Thermal loading can produce large forces
- Why not use applied thermal loading to control structural deformations?

There are several problems associated with use of applied temperatures. The thermal mass of a structure may cause a large time delay before there is a significant response. There may also be a large power consumption, because of the indirect way of converting thermal to strain energy. Finally, the actuator itself is a question.

Problems with Use of Applied Temperatures

- Time lags due to thermal inertia
- Possibly high power consumption
- What can be used as actuators?

Fortunately, there exist semiconductor devices that can act as a heat pump when voltage is applied. They are similar to the devices used in RTG's (radioisotope thermoelectric generators) used to power many spacecraft. These devices are reversible, and may be used as an actuator on a properly designed structure.

Because of finite physical properties, these thermoelectric devices have a finite response time. In addition, a structure must use a relatively large coefficient of thermal expansion to be controlled adequately.

Thermoelectric Actuators

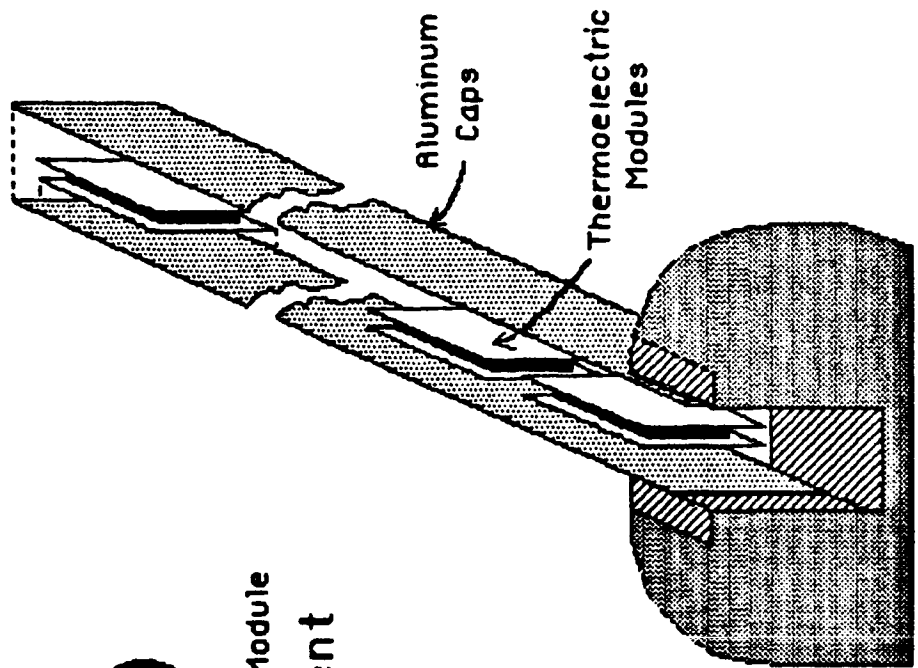
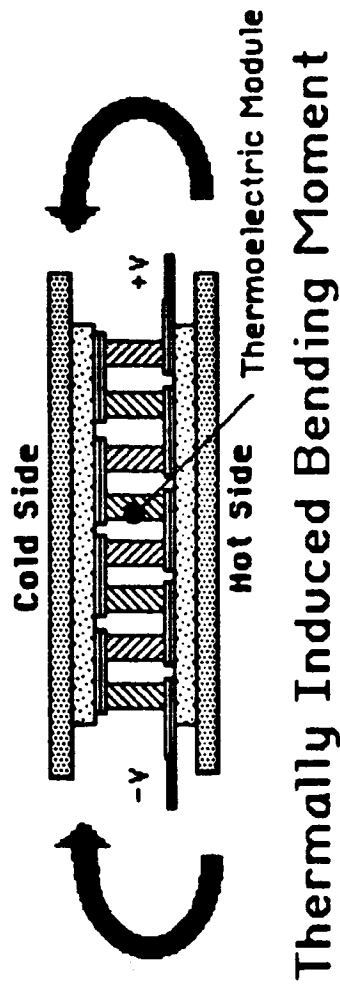
- Used in RTG's as electricity generator
- Reversible – if current is applied, device becomes a heat pump
- May be used as a thermal actuator on a properly designed structure

Drawbacks to their use

- Finite response time due to thermal inertia
- Structural design must use relatively high α materials for maximum effectiveness

These figures show schematically what we employ in our experiment. The first shows that when the thermoelectric device is turned on, it pumps heat from one side of the beam to the other. This creates a bending moment, which will displace the beam.

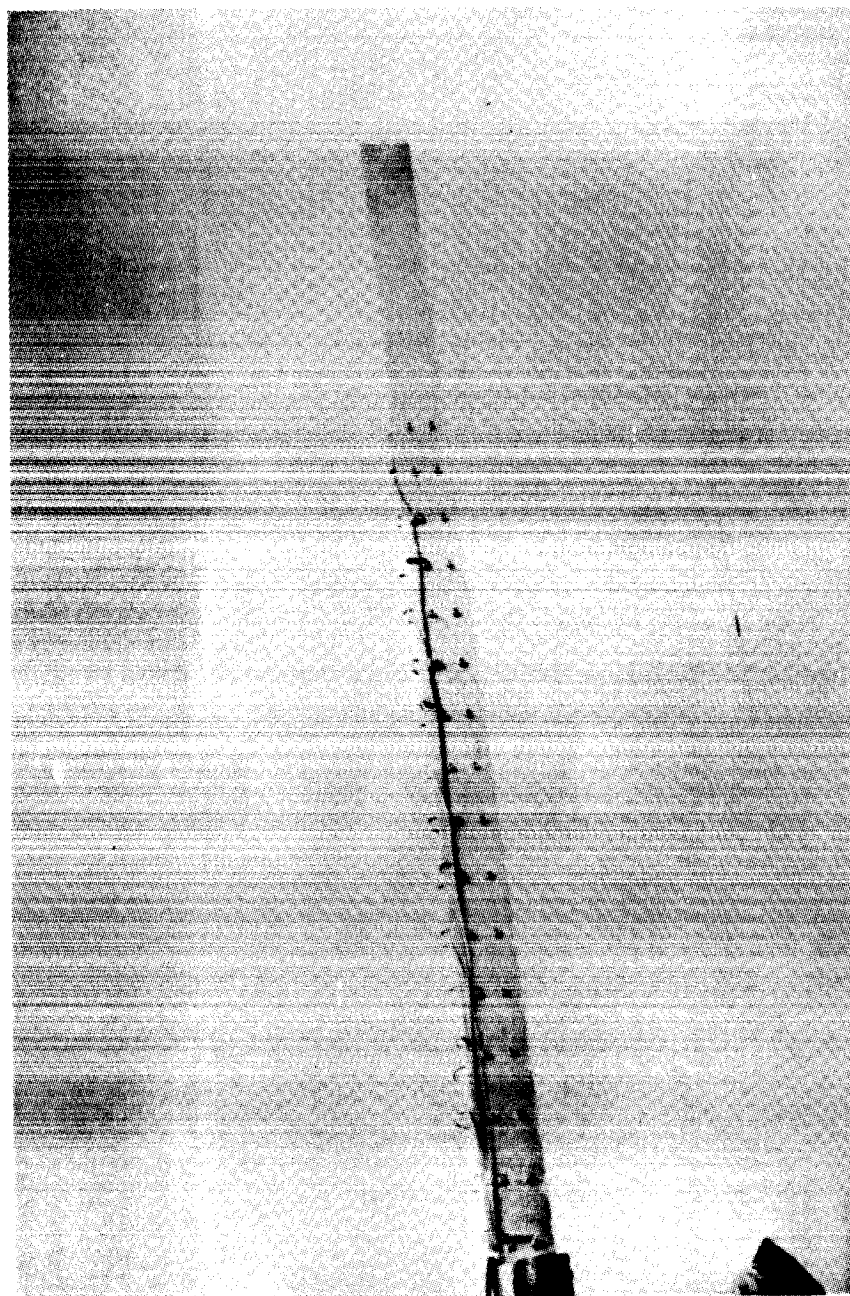
The second illustration shows an exploded view of our experimental beam. It consists of two aluminum caps separating a number of thermoelectric devices. The two caps are bolted together with a number of screws and bolts. The beam is approximately 80 cm long.



This photograph shows a side view of the beam. It is securely clamped in a heavy vise. The rule underneath is six inches long.

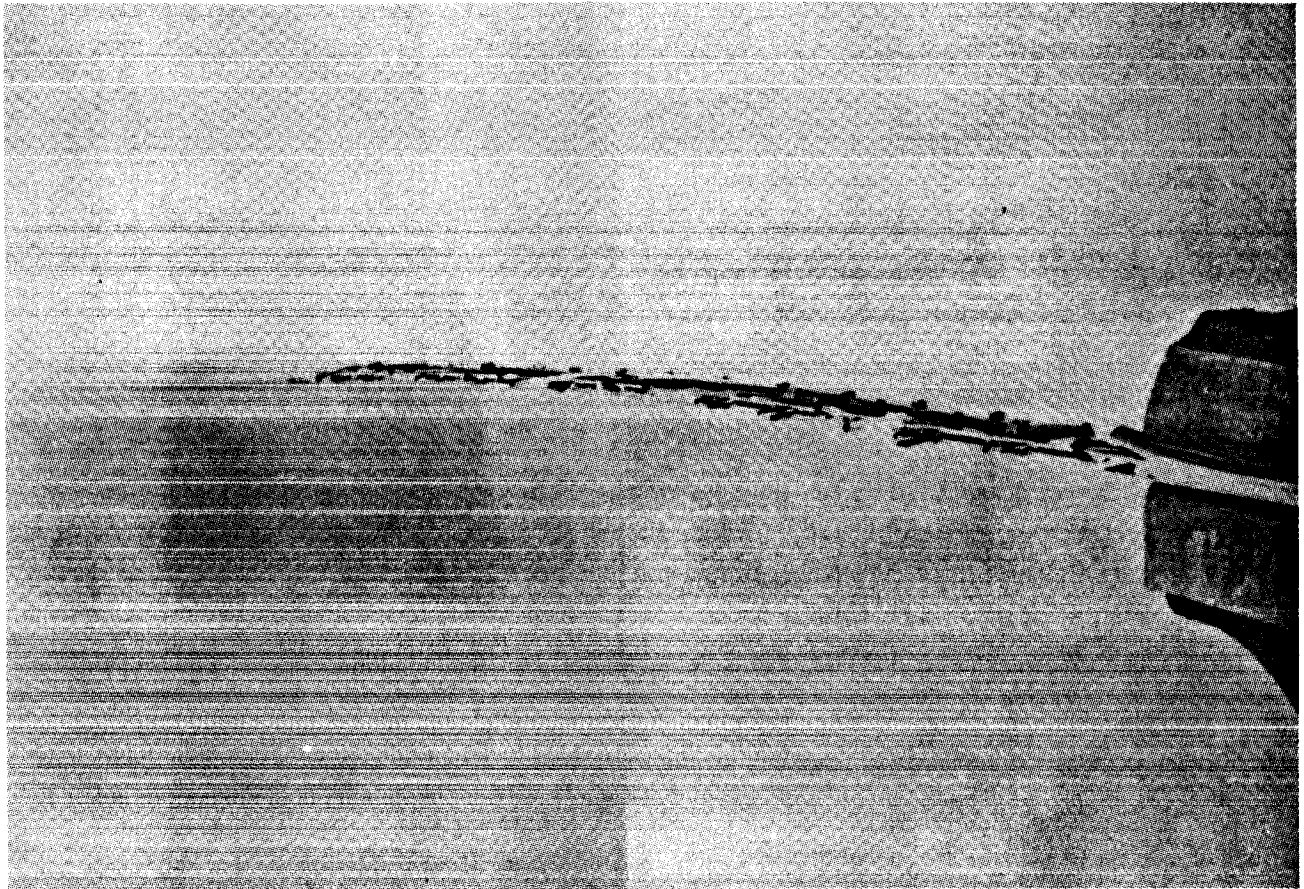
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Photograph of Thermoelectric Beam



ORIGINAL PAGE IS
OF POOR QUALITY

This photograph shows the beam statically deflecting. The tip deflection is approximately 5 cm, on an applied 24 volts.



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**Static Deflection
from
Thermal Gradient**

The equation of motion of the beam is the standard fourth-order Bernoulli-Euler representation, with the exception of the term on the right hand side, which is found from energy considerations. The bending moment M_T is represented as a time function multiplying a step function which turns on at the beginning of the actuators and off at their end. If the deflection of the beam is separated into time and space functions, this results in a modal time function equation whose right hand side is a forcing term dependent on the slope of the (mass-normalized) modeshape at the two ends of the actuators, and the time history of the applied moment. For later analysis, it is convenient to take the Laplace Transform of the equation.

Equation of motion for beam

$$m(x) \frac{\partial^2 w(x, t)}{\partial t^2} + \frac{\partial^2}{\partial x^2} \left[EI(x) \frac{\partial^2 w(x, t)}{\partial x^2} \right] = \frac{\partial^2 M_T(x, t)}{\partial x^2}$$

$$M_T(x, t) = M_T(t) \cdot [H(x_1) - H(x_2)]$$

$$w(x, t) = \sum_{n=1}^{\infty} \varphi_n(x) \cdot \xi_n(t)$$

$$\xi''(t) + 2\zeta\omega\xi'(t) + \omega^2\xi(t) = M_T(t)[\varphi'(x_2) - \varphi'(x_1)]$$

$$[s^2 + 2\zeta\omega s + \omega^2]\xi(s) = M_T(s)[\varphi'(x_2) - \varphi'(x_1)]$$

To determine the time dependence of the applied moment, we must analyze the thermal time history of the beam. Its temperature history is determined by its heat capacity Mc . We further assume that the heating $Q(s)$ is proportional to the applied voltage $V(s)$. The $1/s$ dependence signifies that the thermal mass acts as an integrator.

The bending moment is calculated in the normal fashion, i.e., by integrating the strain across the section of the beam. The magnitude of the bending moment is found by substituting the thermal time history found earlier.

Thermal Equations

$$\frac{T(s)}{\frac{1}{2}Q(s)} = \left(\frac{1}{Mc} \right) \frac{1}{s}$$

$$Q(s) = C_{QV} \cdot V(s)$$

$$T(s) = \left(\frac{C_{QV}}{2n_s \rho A \ell_a c} \right) \frac{V_c(s)}{s}$$

Calculation of bending moment:

$$M_T(t) = \iint_A E \alpha T(z, t) z dA$$

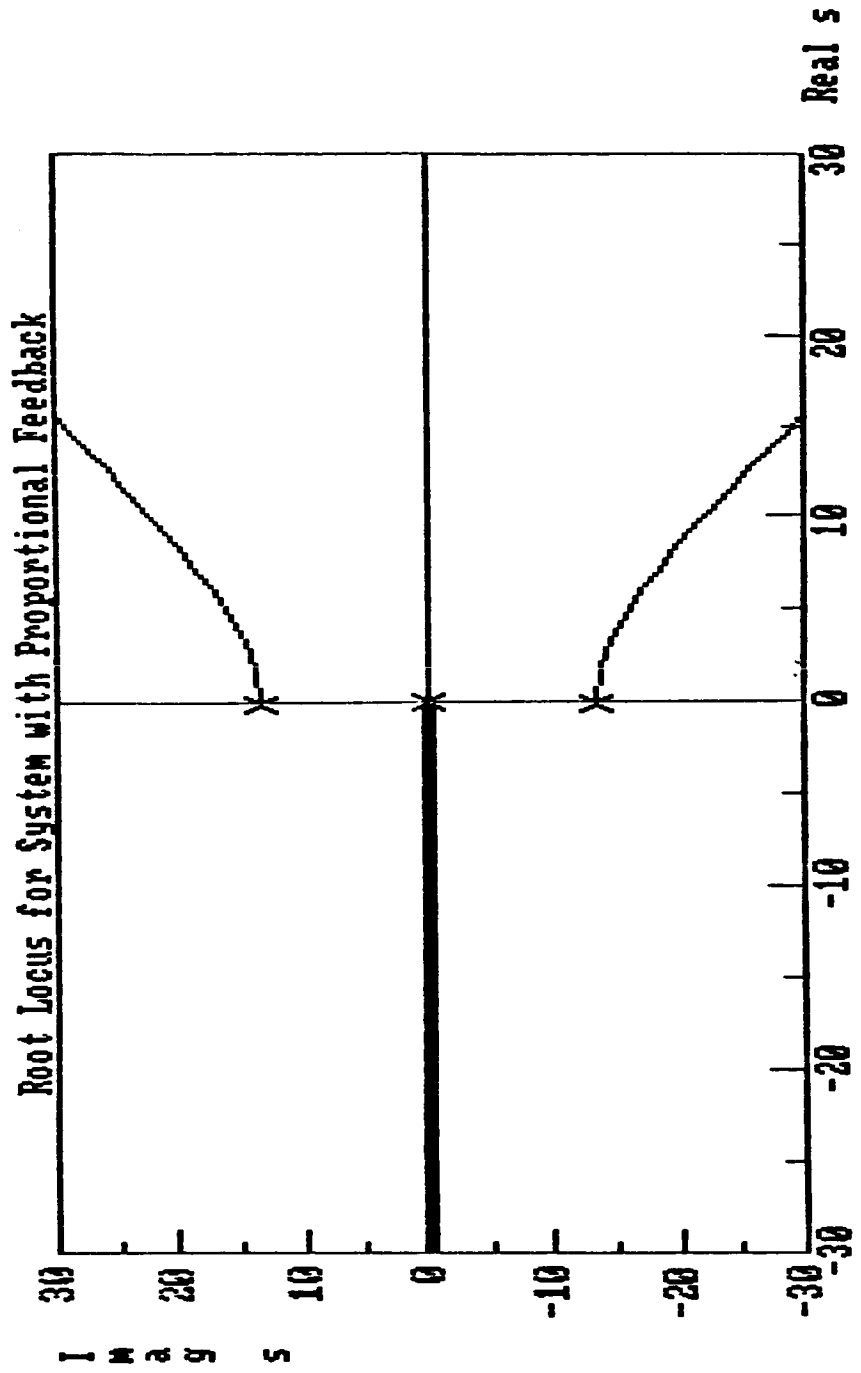
$$M_T(s) = \frac{E \alpha d C_{QV}}{\rho n_s \ell_a c} \frac{V_c(s)}{s}$$

When the bending moment relation is substituted into the beam equation, the open loop system equation results. It has two oscillatory roots in addition to a root at the origin. If proportional feedback is employed to attempt to control the system, the system goes unstable. This is verified by the root locus diagram, which shows that the system must be unstable with proportional feedback.

Open Loop System Equation

$$\frac{\xi(s)}{V_c(s)} = \frac{C}{s(s^2 + 2\zeta\omega s + \omega^2)}$$

Simple feedback leads to unstable system



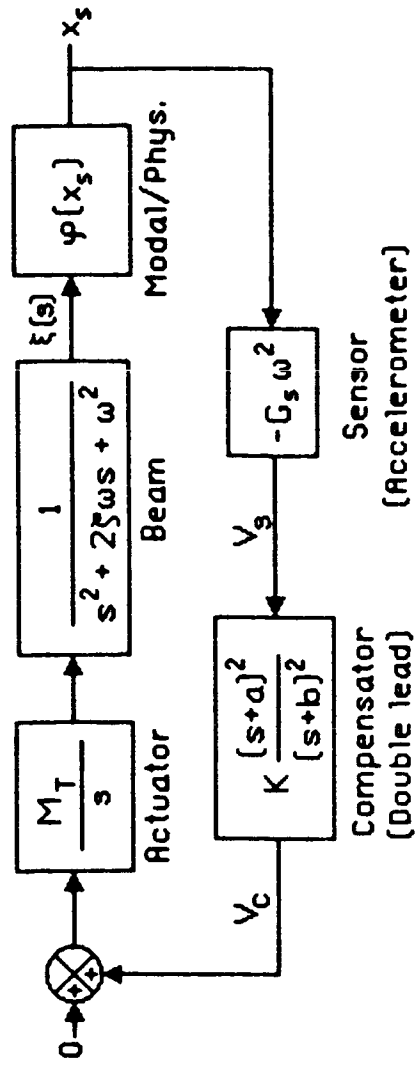
Because of the system behavior, more elaborate compensation is necessary to provide satisfactory behavior. If double lead compensation is added to the system, we can improve the performance. This results in the closed-loop block diagram shown.

Compensation Required

- Double lead compensation can stabilize, i.e. use

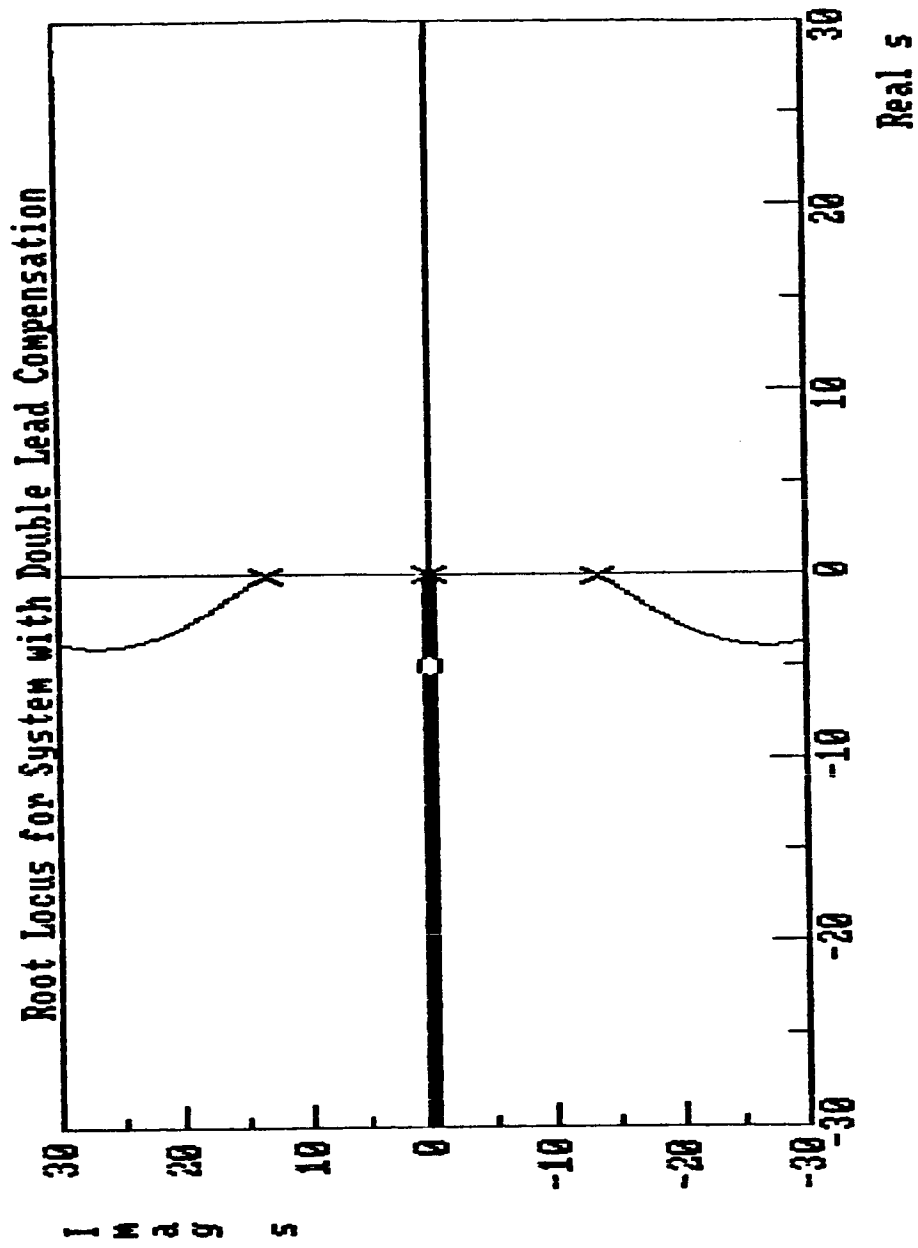
$$C(s) = K \frac{(s+a)^2}{(s+b)^2}$$

Closed-Loop Block Diagram



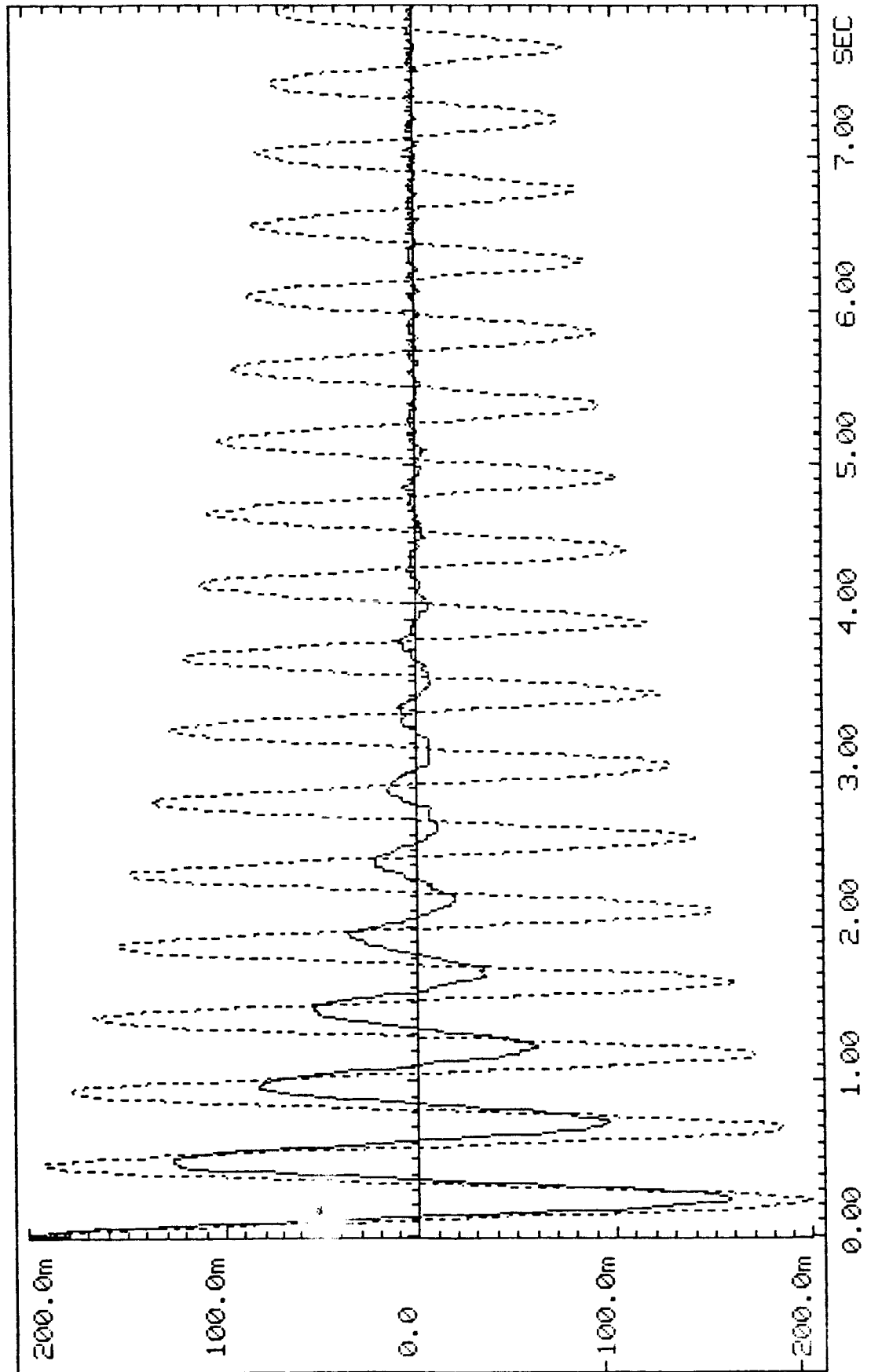
A plot of the closed loop poles is shown. Here we can see that all of the poles move into the left half plane with an increase of gain. We thus expect higher damping than exists in the open-loop system.

Closed Loop Root Locus



This plot shows the *measured* time history of the thermoelectric beam system. The dotted lines show the open loop free decay of the system, while the solid lines show the closed loop decay. One can observe a large increase in the system damping ratio, as expected.

JPL Performance of Open-Loop and Closed-Loop Systems



This table presents the results of the experiment. The system damping ratio has increased from 0.82% to 7.4%, nearly an order of magnitude. The frequency of oscillation has decreased slightly. Most importantly, the settling time factor has increased dramatically. This means that vibrations will be suppressed much faster in the closed-loop system.

Summary of Open-Loop vs. Closed-Loop Performance

System Type	Damping Ratio ζ	Frequency f (Hz)	Settling Time $\zeta\omega$
Open Loop	0.82%	2.154	1.502
Closed Loop	7.4%	2.078	12.61

We have shown that the thermoelectric device is a feasible actuator, and may effectively be used to control structures, provided the structure has a relatively low thermal inertia. The control law only depends on the open-loop system natural frequency.

CONCLUSIONS

- Feasibility of thermoelectric actuators shown
- Damping ratio of system increased by an order of magnitude
- Control law only loosely depends on system frequency

Future work in the field of thermoelectric actuators should address the following topics: power consumption, multimode control, and optimizing structural parameters (particularly thermal parameters). Our work will continue in these areas.

Recommendations for Future Work

- Thermoelectric power consumption
- Multi-mode control
- Optimal system definition (e.g. materials and geometry)